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MODELING OF RF MEMS SWITCHES FOR APPLICATION IN COMMUNICATION SYSTEMS

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Abstract: *Nowadays, the microelectromechanical system (MEMS) technology is emerging as a very promising technology for modern communication systems. An overview of properties, application areas and modeling of RF MEMS switches is presented in this paper, with a focus on the applications in the reconfigurable and adaptive mobile phones as well as in satellite communications. Several modeling techniques are discussed, with special attention paid to the artificial neural network (ANN) modeling.*

Keywords: *RF MEMS, switch, ANN, communication, modeling*

1. Introduction

Today's communication and other microwave systems rely to a great extent on new high performance RF and microwave devices and circuit components. They enable a miniaturization of components according to the demand of integrating more and more functionalities by reducing the overall size of the system at the same time. RF MEMS are novel components which exhibit this potential [1].

RF MEMS (microelectromechanical systems) are RF components and devices, which exhibit mechanically movable parts and thus enable a change of topology. One of the first examples developed in 1995 [2,3] was an electrostatic actuated RF MEMS shunt switch (see Fig. 1).

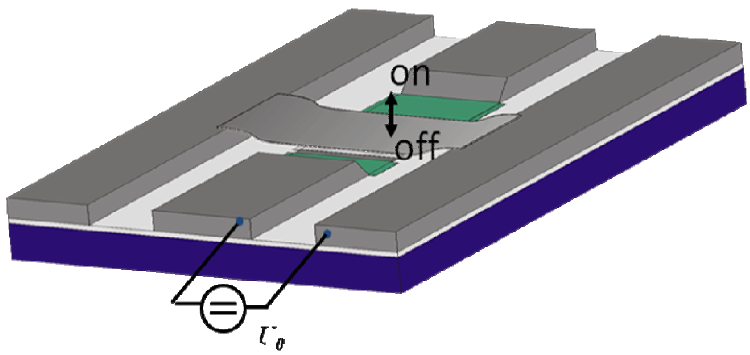

Fig. 1. *Principle sketch of an electrostatic actuated shunt switch in CPW*

Here the ground of the coplanar waveguide is connected by a very thin membrane (~ 1 μm thickness). If a DC voltage is applied between ground and signal line, the membrane is pulled down by the electrostatic force and shortens the signal line.

Since these first developments rapid advances could be observed in this field. Many different components like phase-shifter, reconfigurable antennas, matching networks, switch matrices, tunable filters etc. based on MEMS switches have been introduced as well as other components like varactors, which operate based on the change of topology of the moving membrane. Except the fact that they allow multiband operation due to their ability to reconfigure its topology, they are small in size, can be integrated, offer high linearity and a very low power consumption in all switching states compared to their electronic counterparts like PIN diodes or MESFETs. Regarding their ability of power handling and reliability, big improvements can be observed in the last years. Switches able to handle up to 20 W and operating cycles of 10^{12} have been reported. In general mature technologies now exist and switches and other RF MEMS components for the commercial market are produced by several companies. Application areas are automotion, where broadband switches can be used for switching operations in network analyzers, base stations, where a need of highly linear components is evident. For satellite communication switches and switch matrices offer a tremendous reduction in size compared to the mechanical components used up to now, combined with a low need for DC power supply, what is favorable for satellites staying in the orbit up to 15 years or more. Also the ability for reconfigurability is very much interesting for space applications. It allows changing frequency ranges or other application during operation in the orbit, which will arise if new services are demanded during the lifetime of a satellite, which could not be foreseen during the launch of the satellite.

On the other hand, for these advanced RF and microwave devices there is often a lack of appropriate models which would enable efficient optimization and design process. Therefore, the development of innovative modelling techniques that would provide accurate and reliable models is the key issue in modern circuit design. This paper is aimed at demonstrating smart modelling techniques of particular state-of-the-art RF and microwave devices, based on artificial neural networks.

2. RF MEMS application for communication

If we consider typical scenarios for introduction of RF MEMS in communication systems, front-ends, switching networks [4] or reconfigurable antenna arrays or reflect arrays [5] are the most common candidates.

In a typical communication front-end several possibilities exist to make use of RF MEMS components (see Fig. 2). Except the direct switches employed in such a front end, which could be realized by RF MEMS, there are already diplexers to distinguish between receive and transmit path with high selectivity, based on acoustic principles like SAW and BAW filters, which offer superior functionality compared to conventional filter elements. Other possibilities to employ MEMS components are the tunable filters to select between different frequency bands and reconfigurable matching networks attached to input and output of LNA and power amplifier in the receive and transmit path. Of rising interest is also the insertion of an impedance tuner close to the antenna section, in order to correct any mismatch occurring by environmental changes (hand on the antenna, hand close to the antenna etc.). By a better matching the radiated performance is improved and the power consume reduced, thus increasing the life time of the battery [6].

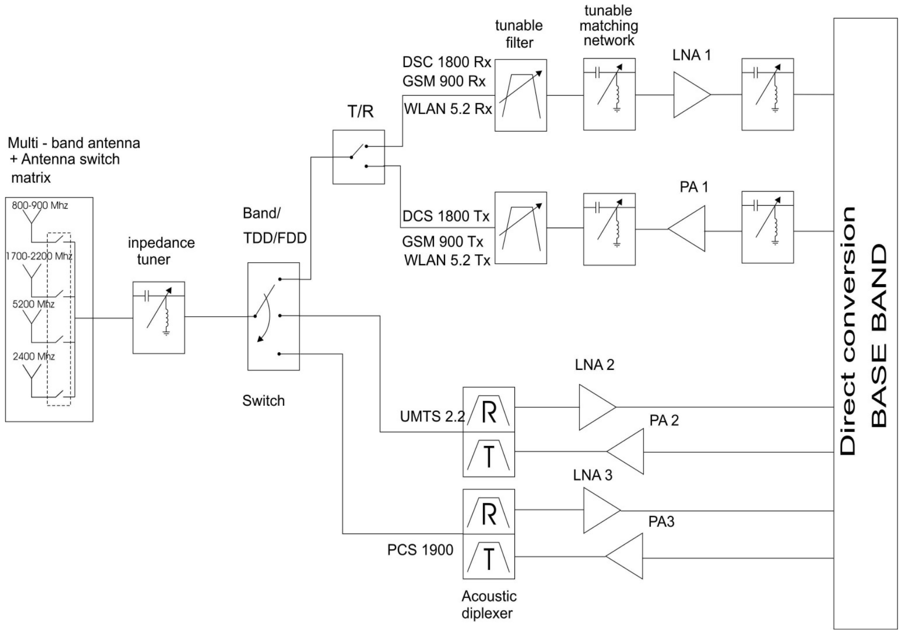

Fig. 2. *Principal sketch of a communication front end employing RF MEMS components*

A different field of application are switching matrices or networks aimed at switching communication channels in satellite communication (see Fig. 3). In the approach of a 16 by 16 matrix shown above, small 2 by 2 switching matrices are arranged in a planar Benes architecture. The single silicon switches are embedded into a multilayer LTCC substrate to arrange the RF and DC connections in different layers to avoid mutual disturbances and coupling.

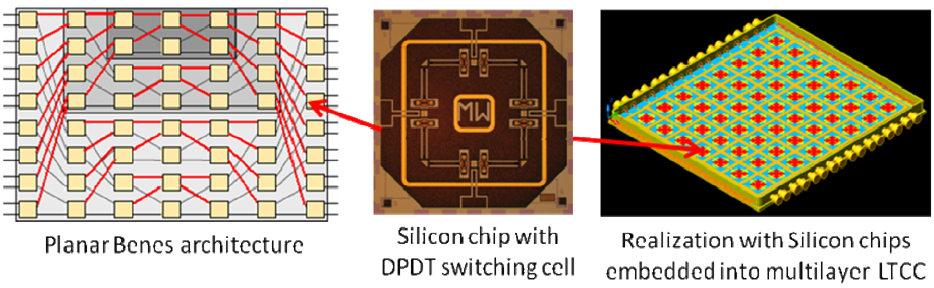

Fig. 3. 16 *by 16 switching network in planar Benes architecture, realized by integrated 2 by 2 RF MEMS DPDT switching cells [7]*

All mentioned applications have in common, that a certain number of RF MEMS switches are integrated together with other circuit components. As RF MEMS switches are in general three-dimensional components, a full-wave analysis is required to determine their performance. However, embedded in a much larger structure a full-wave analysis of the entire configuration is not possible any more. Here circuit models have to be employed to account for the performance of the MEMS.

3. RF MEMS analysis and synthesis

The analysis of a single RF MEMS switch, considering the real topology, what means exact height and width of all layers, perforation of membrane (see Fig. 4) etc. is only possible using 3D simulation tools like CST or HFSS.

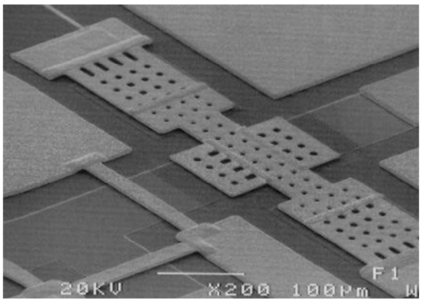

Fig. 4. *Photograph of topology of a series ohmic clamped-clamped beam switch in CPW [8]*

However, some of the parameters regarding thickness of the membrane, the existence of contacting bumps or other shape variations are very much important for the reliability of the device, but have only minor impact on the electrical performance. Therefore, simplified models can be used. Also the simulation with 2.5D solvers like AWR or ADS Momentum is a possible option, as the lateral dimensions of a typical switch are usual higher by orders than the thickness of the different layers employed.

However, for a complete analysis of the structure a multiphysical simulation is needed to calculate switching voltages or determine the switching speed. Some of the tools mentioned above now offer multiphysical calculation modules to account for temperature behaviour or mechanics, however, not all of the added functionalities operate satisfactorily to the same extend, as the EM solvers do. Therefore the typical way of analyzing is the use of different tools requiring different input parameters etc., what can make the development process quite tedious.

If many switches are integrated into the same substrate or interact in a big array or system, the full-wave analysis is not possible any more. The switches only can be described in a circuit simulation by means of pre-computed S-parameters or by developing a proper equivalent circuit model, derived from measurements or full-wave simulations. A problem is that the equivalent circuit parameters have to be derived by fitting for any geometry variation of the switch, as analytic formulas to describe the elements are not accurate enough.

Moreover, if the top-down optimization of a systems gives certain requirements for the employed RF MEMS components, the synthesis of the geometrical parameters for a given performance is not straight-forward. Therefore fast methods are needed to give results for varying geometrical parameters as well as inverse procedures, which relate the geometrical properties to given requirements (resonance frequency of a capacitive shunt switch, as an example). Also fast means to relate electrical and mechanical parameters without using different tools for any re-design of an existing topology in order to adjust for a different frequency range are wanted to speed up design procedures.

A solution to these needs can be the application of artificial neural networks (ANNs) [9] for deriving proper models for different switch types and to relate different sets of input parameters to the desired output quantities.

4. Artificial Neural Networks

Among the most frequently used structures of the artificial neural networks is the multilayer perceptron (MLP) artificial neural network (ANN) shown in Fig. 5. An MLP ANN consists of an input layer (layer 0), an output layer (layer N_L) as well as several hidden layers.

Input vectors are presented to the input layer and fed through the network that then yields the output vector. The *l*-th layer output is:

$$\mathbf{Y}_l = F(\mathbf{W}_l \mathbf{Y}_{l-1} + \mathbf{B}_l) \tag{1}$$

where $\mathbf{Y}_l$ and $\mathbf{Y}_{l-1}$ are outputs of *l*-th and (*l*-1)-th layer, respectively, $\mathbf{W}_l$ is a weight matrix between (*l-1)*-th and *l*-th layer and $\mathbf{B}_l$ is a bias matrix between (*l-1)*-th and *l*-th layer. Function F is an activation function of each neuron and, in our case, is linear for input and output layer and sigmoid for hidden layers:

$$F(u) = 1/(1+e^{-u}) \,. \tag{2}$$

An ANN learns relationship among sets of input-output data (training sets) that are characteristics of the component under consideration. For this purpose, several algorithms have been developed. One of the basic training algorithms is *bacpropagation* algorithm, which can be briefly described as follows. First the input vectors are presented to the input neurons and output vectors are computed. These output vectors are then compared with desired values and errors are computed. Error derivatives are then calculated and summed up for each weight and bias until whole training set has been presented to the network. These error derivatives are then used to update the weights and biases for neurons in the model. The training process proceeds until errors are lower than the prescribed values or until the maximum number of epochs (epoch - the whole training set processing) is reached. There are also modifications of this algorithm which have higher convergence than the *backpropagation* alghorithm, as *quasi Newton* or *Levenberg-Marquardt* algorithms [9].

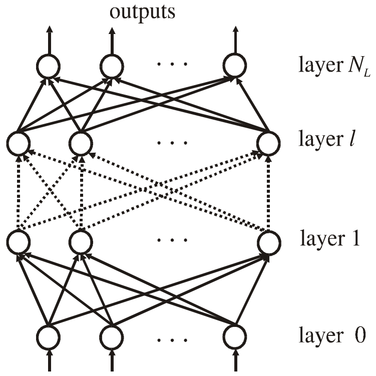

Fig. 5. *MLP neural network*

The most important feature of ANNs is their generalization capability i.e. the capability to provide the correct response even for the input values not presented to the ANN in the training process. In that way, the developed models can be used for a reliable prediction over a wide range of input parameters.

Unlike complex time-consuming electromagnetic models, once developed neural models give responses practically instantaneously because response providing is based on performing basic mathematical operations and calculating elementary mathematic functions (such as an exponential or hyperbolic tangent function). Neural networks have the capability of approximating any nonlinear function and the ability to learn from experimental data. Therefore, it is possible to develop neural model from source-response data points without the knowledge about the physical characteristics of the problem to be solved.

Despite ANN modeling requires sometimes the extensive time and effort to prepare the training datasets, the learning and generalization abilities and their speed qualified the ANNs as a competitive tool for smart modeling in different areas, and especially for modeling of RF and microwave devices [10]-[18].

5. Application of ANNs for RF MEMS modeling

As mentioned above, several full-wave numerical methods are currently being used for RF MEMS modeling. Although these methods provide necessary accuracy, they are generally limited to a single analysis for a specific structure, and their computational overhead (running time, memory) becomes extensive when a number of simulations with different mesh properties are needed [15]. On the other hand, ANN based algorithms have a great advantage in reducing the computational cost, especially when implemented within a circuit simulator that has integrated tuning and optimization options. Based on the massively parallel nature of a neural network, which is capable of modeling nonlinear mappings of multiple input/output variables, this approach has provided an accurate device characterization and efficient prediction of unknown input-output relationships with low computational overhead. Thus, it allows fast calculation of output values for a set of arbitrary input parameters.

There are several papers reporting applications of ANNs for RF MEMS switch modeling [15]-[18]. The results presented in the mentioned papers will be analyzed in the text bellow.

An ANN based approach for modeling and design of RF MEMS switches is proposed in [15]. A CPW shunt RF MEMS switch is selected as an example for which the methodology is demonstrated. The proposed modeling procedure starts with a full-wave simulation for both device characterization and ANN datasets generation. The switch's width and length are selected as ANN input variables while the insertion and return loss for up to the W-band are output variables (Fig. 6). It is shown that the developed ANN model preserves the accuracy of the full-wave FEM model while having large savings in the running time (about 600 times reduction).

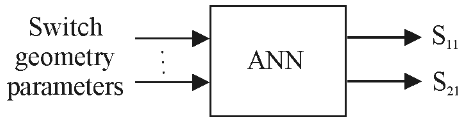

Fig. 6. *ANN model for calculation of RF MEMS S-parameters*

Similar approach is proposed in [16]. The paper presents the design of a low actuation RF MEMS shunt switch by using two short high impedance lines. After that, the neural networks are employed for determining S_{11} parameter for a RF MEMS shunt switch. The length of the lines and the height of the gap have been chosen as ANN inputs. The outputs are 8 different points from 0 to V band of the S_{11} (2GHz, 11GHz, 21GHz, 36GHz, 46GHz, 56GHz, 61GHz, and 66GHz). The outputs are considered independently. Namely, eight different ANNs are trained, each generating one S_{11} output associated with a certain frequency. It was shown that the results of the developed ANN were accurate. This method provides a significantly less running time for simulations of the switch.

The mechanical and electric characteristics of RF switches significantly depend on theirs structural parameters, therefore it is important to design and optimize the structure of the switches. A kind of RF MEMS switch structure with special cantilevered beam section is proposed in [17]. The structure parameters of the cantilevered beam are optimized with the methods of orthogonal experiment, BP Neural Network and Genetic Algorithm (GA). In the paper, the BP neural network is applied to find the relationship between the structure parameters in cantilevered beam and the first resonate frequency of the cantilevered beam MEMS switch, as shown in Fig. 7.

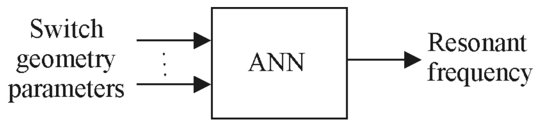

Fig. 7. *ANN model for RF MEMS resonant frequency determination*

In the paper [18] an efficient approach based on ANN for analyzing the losses in ON and OFF state of lateral RF MEMS series switch by calculating the S-parameters is proposed. The variations of S parameters (return and insertion losses) with respect to change in the equivalent circuit parameters for the MEMS series lateral switch operate up to 25GHz are investigated (Fig. 8). The presented results obtained by the neural models are in very good agreement with the theoretical results available in the literature.

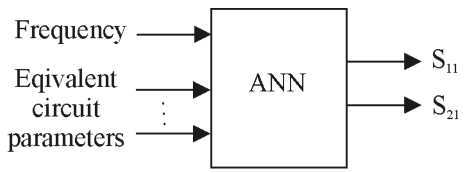

Fig. 8. *ANN RF MEMS model for S-parameters*

Since the presented neural models have good accuracy, require no tremendous computational efforts and less background information about bridges, they can be very useful for the development of fast CAD algorithms. A distinct advantage of neural computation is that, after proper training a neural network completely bypasses the repeated iterative processes when new cases are presented to it.

6. Conclusion

RF MEMS switches are key circuit elements in the field of microwave control. They have wide applications in phase arrays and configurable apertures for defense and telecommunication systems, switching networks for satellite communication. RF MEMS switches have several advantages over PIN diode and FET switches such as low insertion loss, high isolation, excellent compatibility with current microwave and mm-wave circuits. Because of those significant advantages mentioned above, RF MEMS switches are increasingly under focus.

However, current researches of RF MEMS switches are mostly concentrated on various new structure or new materials, while optimization analysis of MEMS devices lack enough study.

There are several numerical methods that can be used to model RF MEMS switches. Although these methods provide accuracy, their computational overhead such as running time and memory requirement become complex when a number of simulation for determination of various device parameters are needed.

In order to overcome these shortcomings, ANN based approaches for simulation, design, and optimization of RF MEMS switches have been proposed. Owing to their ability to learn and generalize complex input/ output relationships with massively parallel computation process, ANNs are recognized as a viable computer aided design technique for modeling, design and optimization of RF MEMS switches.

However, the presented approaches are very basic and consider modeling only a part of the characteristics of RF MEMS switches. The further research activities will be directed to the development of new models of RF MEMS switches which would combine both electrical and mechanic behavior of the devices. Moreover, applications of ANNs for building fast and efficient procedures for optimization of RF MEMS switches will be investigated.

Acknowledgements

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Sadržaj: *U poslednje vreme, tehnologija mikroelektromehaničkih sistema pojavljuje se kao veoma perspektivna tehnologija za savremene telekomunikacione sisteme. U ovom radu dat je pregled osnovnih karakteristika, oblasti primene i tehnika modelovanja RF MEMS prekidača, sa posebnim akcentom na aplikacije koje se odnose na rekonfigurabilne i adaptivne mobilne telefone, kao i na satelitske komunikacije. Prikazano je nekoliko tehnika modelovanja ovih uređaja, a posebna pažnja posvećena je modelovanju korišćenjem veštačkih neuronskih mreža.*

Ključne reči: *RF MEMS, prekidači, veštačke neuronske mreže, telekomunikacije, modelovanje*

MODELOVANJE RF MEMS PREKIDAČA ZA PRIMENE U TELEKOMUNIKACIONIM SISTEMIMA

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